BayouAcoustics
176 Bald Eagle Drive
Abita Springs, LA 70420

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Characteristics of Fishes with the Potential to Cause Acoustic Clutter off Oregon and Washington during the Summer of 2012

Richard H. Love

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Dr. Robert Headrick, Code 322OA
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In the summer of 2012, the Naval Research Laboratory (NRL) conducted an experiment off the coasts of Oregon and Washington to investigate acoustic clutter caused by aggregations of fish. Two surveys and an experiment that were focused on the fish themselves were conducted in and near the NRL experiment area at about the same time. These showed that Pacific sardine and Pacific hake were abundant in and around the NRL experiment area and provided information on their characteristics that are pertinent to the clutter experiment. This report discusses these characteristics, including abundances, geographic and depth distributions, and the sizes of individual fish and fish aggregations.

15. SUBJECT TERMS
Biological clutter; fish schools; fish aggregations; Pacific sardines; Pacific hake

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CHARACTERISTICS OF FISHES WITH THE POTENTIAL TO CAUSE ACOUSTIC CLUTTER OFF OREGON AND WASHINGTON DURING THE SUMMER OF 2012

INTRODUCTION

Fish can adversely affect the performance of Naval active sonar systems. Widely dispersed fish can cause reverberation that can mask target echoes. Groups of fish can produce echoes that can cause clutter or be mistaken for targets. The Naval Research Laboratory (NRL), supported by BayouAcoustics, conducted an experiment off Oregon and Washington during the summer of 2012 as part of an effort sponsored by the Office of Naval Research (ONR) to mitigate the effects of biological clutter

Prior to the NRL experiment, two species of fish, Pacific sardine (*Sardinops sagax*) and Pacific hake (*Merluccius productus*) (also known as Pacific whiting), were identified as the species mostly likely to cause significant clutter during the experiment because they were, by far, the most abundant fishes in the region. References 1 and 2 provided background information on Pacific sardine and Pacific hake and presented data from several years prior to 2012 on characteristics of these species that could affect the experiment. These characteristics included abundance, summertime geographic and depth distributions, aggregational tendencies, and sizes of individual fish.

The present report examines information obtained during the summer of 2012 to demonstrate that, in fact, Pacific sardine and Pacific hake were abundant in the experimental area during the experiment. The report also describes characteristics of the two fish stocks that pertain to the experiment. The information comes primarily from 2012 fishery surveys, 2012 fishery catch statistics, fish related experiments, and official assessments of the status of the Pacific sardine and Pacific hake stocks for 2012 and 2013. The report does not generally repeat the background material found in References 1 and 2 but it does present some information from previous years, and from 2013, to put the 2012 data in perspective.

CONCURRENT EXPERIMENTS AND SURVEYS

Much of the Pacific sardine and Pacific hake stocks undertake annual north-south migrations. They migrate in late spring from off California to the Pacific Northwest to feed during the summer. In the fall they migrate back to California to spawn during the winter and spring. The extent of the northward migration depends on oceanic conditions, the sizes of the stocks, and the ages of the fish. The fish move farther north when the ocean is warmer and when the stock is bigger and older. Larger fish travel farther than younger, smaller fish.

The year-to-year variations in annual migrations make it difficult to know accurately what the situation might be during any single year with regard to these fish. Fortuitously, in addition to the NRL experiment, there were several other experiments and surveys concerned with Pacific sardine and/or Pacific hake during the summer of 2012: an aerial survey of sardines, a combined echo sounder/trawl survey of sardines and hake, a Canadian echo sounder/trawl survey of hake, and an experiment on hake and squid. These experiments and surveys allow a clear picture to be developed with regard to Pacific sardine and Pacific hake in the NRL experiment area during the summer of 2012.

The NRL experiment was conducted from July 26 through August 6 on the R/V New Horizon. Figure 1 shows the experiment area. The original area was much larger, extending both north and south, as well as into shallower water. However, due to restrictions imposed by marine mammal regulations, the operating area was reduced and NRL had to operate its acoustic system in waters deeper than 200 m and look shoreward. NRL conducted clutter measurements within the boxes shown in Figure 1 from July 27 through 31 and on August 5. From August 1 through 4, the Johns Hopkins Applied Physics Laboratory (JHU/APL) conducted a bioacoustic absorption experiment.

The Northwest Aerial Sardine Survey (NWASS) has conducted annual summer surveys of Pacific sardine since 2009. The 2012 survey was conducted from July 31 through September 13. [3] The survey consisted of two elements. The first element was a series of 33 nm east-west aircraft transects spaced 7.5 nm apart, during which overlapping aerial photographs were continuously taken. The second element was a number of aircraft-directed catches of sardine schools. These catches were used to relate school surface area to school weight and to obtain information on individual fish.

The Northwest Fisheries Science Center (NWFSC) of the National Marine Fisheries Service (NMFS) has been conducting echo sounder/trawl surveys of Pacific hake since 1977. Since 2001, surveys have been conducted biennially. The Southwest Fisheries Science Center (SWFSC) of NMFS conducted echo sounder/trawl surveys of Pacific sardine in the spring of 2006, 2008, 2010, and 2011, and in the summer of 2008. In 2012, SWFSC and NWFSC conducted a joint sardine/hake survey that extended from central California (35.8°N) into Canada (50.8°N) from June 27 through August 23. [4, 5] During daylight hours, the NOAA Ship Bell M. Shimada conducted multifrequency echo sounding along east-west tracks that were nominally 10 nm apart. The tracks extended from approximately the 30 m depth contour to the 1500 m contour or for 35 nm, whichever was greater. At night the Shimada conducted trawls and oceanographic measurements. In addition, the F/V Forum Star conducted trawls along the tracks as directed by the Shimada.

The Pacific Biological Station (PBS) of the Department of Fisheries and Oceans Canada (DFO) conducted a survey of hake off British Columbia from August 9 through September 7 in cooperation with NMFS. [4] The CCGS W.E. Ricker ran a series of daytime echo sounder tracks that began near the southern end of Vancouver Island (48.8°N), overlapping with the northernmost Shimada tracks, and extended to Dixon Entrance, Alaska (55.3°N). The Ricker conducted trawls along the tracks at night. The tracks were east-west and about 10 nm apart along Vancouver Island but farther north their direction and spacing varied.

Scientists from Oregon State University (OSU) and NWFSC conducted an experiment off the coast of Oregon from July 26 through August 10 aboard the R/V Oceanus. The experiment was focused on both hake and squid and consisted of multifrequency echo sounding and fishing. [6] This experiment was conducted in the same general area as the NRL experiment.

A final report has been published for the aerial survey. [3] NWFSC has published a cruise report on the hake component of the joint sardine/hake survey. [4] SWFSC has presented a summary of the sardine component. [5] In addition, data have been presented to Pacific fishery management groups for the purpose of estimating the abundances of sardine and hake in 2012 in order to set fishing catch limits for 2013. [7, 8] OSU has not yet published a report. NWASS, NMFS and OSU have graciously provided some unpublished data.

ABUNDANCES

The primary goal of most fisheries research is the determination of abundance of commercially important fish species. Accurate abundance information provides a scientific basis for stock management. For management purposes, the fisheries research community has grouped fish off the West Coast in several categories. The categories of interest are Coastal Pelagic Species (CPS), Highly Migratory Species, Groundfish, and Salmon. Off Washington and Oregon, Coastal Pelagic Species include Pacific sardine, Pacific herring, northern anchovy, Pacific (chub) mackerel, and jack mackerel. The only significant Highly Migratory Species off Washington and Oregon is albacore tuna. Groundfish include demersal and semi-demersal fishes. The semi-demersal fishes include Pacific hake, cods, sablefish and grenadier. Scattering from the bottom normally overwhelms scattering from any demersal fishes, so they are not of interest. Salmon include chinook, chum, coho, pink, sockeye, and steelhead trout.

The frequency and extent of assessments of the abundance of various fish stocks is generally related to their commercial importance or their imperiled status. Because of the commercial importance of Pacific sardine and Pacific hake, extensive assessments of their abundances are conducted annually. These assessments combine fishery data, primarily fish catch statistics, and non-fishery data, primarily the results of scientific surveys, in ever-evolving models to predict abundance. Fishing quotas are then set based on those predictions.

Unless a fish species is of little commercial value, catch statistics are a relatively reliable measure of abundance. Figure 2 shows catches of fishes off U.S. West Coast from 2000 through 2013. The data are primarily from the Pacific Fish Information Network (PacFIN), which is funded by NMFS. [9, 10] PacFIN statistics usually include only those fishes landed ashore. The total catches of all fishes of potential interest except for hake are landed ashore. A significant portion of the hake catch is processed offshore. Offshore hake catches were obtained from Reference 10. Note that these statistics are only for the U. S., they do not count sardines landed in Mexico or hake caught in Canada.

Figure 2 shows that, although the U.S. hake catch fluctuated quite a bit from year to year, it far exceeded that of any other fish in every year since 2000. Between 2000 and 2013, hake accounted for more than half of the total catch weight of all the fishes considered for every year except 2002, when it was 45%. In 2011, it reached a maximum of 71%. Hake also accounted for more than 80% of the groundfish catch in every year since 2000, except 2002, when it was 76%. In 2012, hake were 51% of the total catch and 86% of the groundfish catch.

Figure 2 also shows that the U.S. sardine catch was significantly higher than the catches for all fish but hake, ranging between about 20% and 33% of the catch for every year but 2011, when it was only 14%. Sardine accounted for more than 80% of the CPS catch in every year since 2002, except 2006, when it was 78%. In 2012, sardine were 33% of the total catch and 91% of the CPS catch.

These catch statistics prove that Pacific sardine and Pacific hake were abundant off the U.S. west coast in 2012. They also indicate that these two species were much more abundant than any others.

The official estimates of the abundance, or biomass, of Pacific sardine and Pacific hake stocks are made each year at meetings of the Pacific Fishery Management Council (PFMC). Each year, the assessment models back-calculate abundances for previous years based on all accumulated data. The models use time series of data, so that updated models or data affect not only the current year, but previous years as well.

Pacific Sardine

Figure 3a shows abundance estimates for the Pacific sardine spawning stock for assessments conducted in 2007 through 2014. [1, 7, 11, 12] For sardine, the spawning stock is defined as all individual fish of Age 1 or greater. The values in Figure 3a are the estimated biomass on July 1 of each year.

The Pacific sardine stock was extremely small in the 1970's. It began a recovery in the early 1980's, reaching a peak in 1999 or 2000. The 2007-2010 assessments show the stock peaking in 2000 at about 1.6 MT. The 2011-2014 assessments show it peaking in 1999 at lower levels, between 1.1 and 1.3 MT. All the assessments show the stock decreasing until 2003 and then increasing. Except for the 2011 assessment, which will be discussed below, all of the assessments peak between 1.2 and 1.4 MT. The 2007 and 2008 assessments, which are almost identical, peak in 2004-2005 at 1.2 MT and then decrease through the end of the assessment period. The 2009 and 2010 assessments peak in 2006 at about 1.3 MT and then decrease through the end of the assessment period. The 2012, 2013 and 2014 assessments, which are almost identical, peak in 2006-2007 at almost 1.4 MT and then decrease through the end of the assessment period. For each of the three pairs of assessments, the peak has shifted slightly higher and slightly later in time.

One of the parameters in the assessment models is the estimated numbers of fish at different ages. This number can be especially difficult to ascertain for Age 0 fish. Figure 3b shows the estimated number of juveniles used in the sardine assessments of 2007 through 2014. The numbers for all assessments agree quite well from 2000 through 2004, when they begin to diverge. In general, after 2004, the estimate of juvenile numbers is lowest for the 2007 and 2008 assessments, higher for the 2009 and 2010 assessments, and highest for the 2011 through 2014 assessments. This general increase in juveniles over the period goes a long way to explaining why the peak in the assessments of the adult stock keeps rising and moving later in time. Figure 3b shows that the 2011 estimate of juveniles for 2010 and 2011 is much higher than later estimates. This difference is a major factor in explaining why the 2011 assessment differs from the others.

The Pacific sardine population off the West Coast tends to run in cycles of about 60 years, affected by ocean conditions and fishing pressure, with about 30 years of abundance followed about 30 years of scarcity. The most recent period of abundance began in the early 1980's. [7] Figure 3b shows that the latest estimates indicate that the 2010 and 2011 year classes were very weak. The 2012 and 2013 estimates predicted strong year classes that the following year's estimates significantly reduced. The 2014 estimate predicts a relatively strong 2013 year class compared to 2010 through 2012. Will the 2015 estimate agree? The sardine stock exploitation rate, which is the ratio of total catch to stock biomass, was less than 10% between 2004 and 2010. In 2011, 2012 and 2013, it was between 10% and 19%. [12] The combination of weak year classes and higher exploitation rates is not a positive sign for the stock.

Catch statistics of Pacific sardines off the west coast are reported for six regions: northern Mexico, southern California, central/northern California, Oregon, Washington, and British Columbia. These statistics can provide some additional information about the stock. Since 2000, the sardine catch in northern Mexico has been between 40000 and 70000 mt. In 2012 and 2013, it was about 50000 mt. [11] Since these fish don't migrate to Oregon and Washington, the Mexican catch will not be considered further.

Figure 3c shows catches of Pacific sardine since 2000 for the other five regions. [11] From 2000 through 2002, catches in southern California were between 45,000 and 50,000 mt and dominated the total catch. Since 2002, southern California catches have, except for peaks in 2007 and 2010, generally decreased, reaching a low of less than 7000 mt in 2013. Catches in northern California were below 15,000 mt through 2005, increased to a peak of 35,000 mt in 2007, and remained relatively high in 2008 and 2009. Since 2009, northern California catches have decreased, reaching a low of less than 1000 mt in 2013. Catches in Oregon steadily increased from 2000 to a peak of 45,000 mt in 2005, remained high in 2006 and 2007, decreased from 2007 to 2011, spiked to over 40,000 mt in 2012, and remained high in 2013. Catches in Washington remained below 15,000 mt until they spiked at 35,000 mt in 2012, and remained high in 2013. Catches in British Columbia were less than 5000 mt from 2000 to 2007, steadily increased from 2007 to a peak over 20,000 mt in 2010 and remained high through 2012. In 2013, catches in British Columbia plummeted to zero; not a single sardine was caught.

The scarcity of sardines in California and their absence in British Columbia in 2013 are causing great concern among fishermen in those regions and environmentalists. [13-15] They are worried that that the stock will collapse. However, it is too soon to tell if the stock is entering a long period of scarcity, as it has in the past, or if the 2013 year class is strong enough to cause the peak to shift to later in time again or even allow it to recover as it did from 2004 to 2006 (Figure

3a). Fishermen in Oregon and Washington, who were catching high numbers of fish in 2012 and 2013, did not want to drastically reduce sardine catch limits in 2014 [16], while environmentalists were asking sardine catches to be suspended. [15] PFMC has set catch limits for 2014 that are about 40% of the 2013 limits. [7, 12]

During the NWASS surveys, pilots direct the fishing boats to catch particular schools of sardine. In 2009, 2010 and 2011, the mean percentage of sardine in the schools caught during the NWASS surveys ranged from 99.5% to 99.9%. All schools caught during those three years were at least 97% sardine. In 2012, the mean dropped to 93% and three schools had less than 90% sardine. [3] Hence, although the pilots directed the boats to fish schools that they believed to be totally sardine, there was some occurrence of other species in 2012. Even so, sardine were still, by far, the most abundant and the NWASS catches support the conclusions drawn from the catch statistics.

Pacific Hake

Figure 4a shows biomass estimates for the female Pacific hake spawning stock for assessments conducted from 2009 through 2013. [2, 8] For hake, the estimates consider only adult females. Hence, assuming that there are approximately as many males as females, the total adult biomass should be about double that shown in Figure 4a. The 2009, 2010, 2012 and 2013 assessments agree very well through 2011. The 2011 assessment differs somewhat from the others in 2002 and 2003 and differs significantly after 2006.

The size of the hake stock is primarily driven by occasional strong year classes. In the last two decades of the twentieth century, there were very strong year classes in 1984 and 1999, and strong years classes in 1987 and 1990. Figure 4b shows estimated numbers of juvenile hake since 1998 for the assessments conducted in 2009 through 2013. All the assessments agree through 2004. The 2011 assessment estimated relatively strong year classes in 2005 and 2006, while the others did not. For 2008, the 2009 and 2010 assessments estimated a relatively weak year class, the 2011 assessment estimated a very strong year class, and the 2012 and 2013 assessments estimated a strong year class. For 2010, the 2013 assessment estimated a very strong year class, while the others did not.

Just as with the sardine assessments, one of the inputs to the hake assessment models is the estimated numbers of fish at different ages and, just as with sardines, this number can be difficult to ascertain for Age 0 hake. Thus, the 2011 assessment overestimated the hake stock due primarily to its overestimate of the 2005, 2006 and, especially, the 2008 year classes. Also, the 2013 abundance estimate is higher than the 2012 estimate due to the significant difference in their estimates of the size of the 2010 year class.

Since hake are long-lived fish, a strong year class can dominate the population for a number of years. For example, fish from the 1999 year class still dominated the stock in 2006. [8] If the 2013 estimate of the size of the 2008 and 2010 year classes proves to be correct, they should dominate the hake population for the next several years and it would be expected that the stock will remain relatively high during that time.

Catch statistics by region are not generally very revealing for hake because they only count hake landed ashore and a high percentage of the catch is processed offshore. The processor ships are based in Seattle and can fish anywhere in U.S. or international waters. However, the effect of a strong year class on the distribution of hake catches landed ashore can be seen in Figure 4c. The catch in British Columbia in 2000 was 22,000 mt. It steadily increased to 2004, when it peaked at 125,000 m. This peak was caused by the 1999 year class getting larger and moving into Canadian waters. The decrease after 2004 was caused by these fish steadily being caught or otherwise dying.

Figure 4c also shows that the hake catch in California is low. From 2000 to 2010, it varied between 5000 and 1700 mt. Since 2011, catches of hake in California have been 5 mt or less. The shore-based catches from Oregon and Washington are not too meaningful for total abundance, since most of the processor ships operate off those states.

The Forum Star conducted mid-water trawls during the NMFS survey, fishing at depths where the Shimada determined hake were. Hake comprised 91% of the catch by weight. [17] No other species was more than 4%. The percentage of hake caught supports the conclusions drawn from the catch statistics.

SIZES OF INDIVIDUAL FISH

Pacific Sardine

During the summers of 2009 through 2012 NWASS captured 146 schools of Pacific sardine off the coasts of Oregon and Washington. [1, 3] Lengths were measured for 50 fish from each school; a total of 7300 fish. Mean total lengths of sardines were 22.1 cm in 2009, 22.6 cm in 2010, 23.6 cm in 2011, and 22.3 cm in 2012. Length distributions for each year had a single relatively narrow peak. The tenth percentile was only 4-5% shorter than the mean and the ninetieth percentile was 4-5% longer.

Sardines off Oregon and Washington are Age 2 or older. [7] The 2012 sardine assessment estimated that the 2009 sardine stock of Age

2 or greater fish was dominated by Age 2 and Age 4 fish from the 2007 and 2005 year classes. Figure 3b shows that the 2012 assessment estimated a very strong 2005 year class and a moderately strong 2007 year class. In 2010, Age 2, Age 3 and Age 5 fish from the 2008, 2007 and 2005 years classes were estimated to be about equal. Although the 2012 assessment estimated that the 2008 year class was relatively weak, the 2005 and 2007 year classes were depleted by 2010 so that the three year classes were of similar size. Age 2 and Age 3 fish from the strong 2009 year class were estimated to dominate in 2011 and 2012, respectively.

There appears to be a discrepancy between the mean sardine lengths measured by NWASS and the age distributions in the 2012 sardine assessment. If the sardine stock off Oregon and Washington were dominated by the 2009 year class in 2011 and 2012, one would assume that the fish would have been larger in 2012 than in 2011. This apparent discrepancy will be addressed below.

The 2012 NWASS sardine measurements were supplemented by length measurements on over 5000 fish caught by commercial fishermen. [3] Lengths ranged from 21.0 cm to 25.5 cm, with a mean of 23.0 cm. Modes of the length distributions for both the NWASS-directed catches and the commercial catches were both 22 cm. The difference between the means was due to the commercial catches having a higher percentage of fish larger than 23 cm.

Sardine lengths were measured during the summer 2012 NMFS survey. [5] The modal length was about 23 cm and 99% of the fish were between about 22 and 27 cm.

NWASS also measured sardine weights. Mean weights were 133 gm in 2009, 138 gm in 2010, 166 gm in 2011, and 139 gm in 2012. Weight distributions also had a single peak, with the tenth percentile about 15% lighter than the mean and the ninetieth percentile about 15% heavier.

The sardine assessments use an equation that relates the weight of a fish to, approximately, the cube of its length [1]:

$$W = 0.01234\ L^{2.94825}$$

Weights of 22.1, 22.6, 23.6 and 22.3 cm long sardine are 114, 121, 138 and 117 gm, respectively. Hence, a comparison of the mean lengths and mean weights obtained from the 2009 through 2012 NWASS catches shows that the NWASS fish were about 15 to 20% heavier than the equation predicts. This is most likely because the fish are at their heaviest during the summer feeding season.

The NWASS-directed catches took place over a rather small area in 2012. The NWASS-related commercial catches covered a significantly larger area and the NMFS catches were made from California to Canada. Thus, the commercial catches probably give the best value of mean length for use in calculations related to the NRL experiment. It is reasonable to assume that, since the NWASS-directed catches and the commercial catches were made at approximately the same time, length-weight relationships for fish from both sets of catches would be the same.

Thus, the most probable mean length and weight of sardines in the NRL experimental area during the summer of 2012 were 23 cm and 150 gm, respectively.

Pacific Hake

Data on the sizes of Pacific hake are available since at least 1975. [2, 8] Lengths and weights vary from year to year. These variations show no long-term pattern for fish of Age 8 or less. However, fish of Age 10 or more were significantly longer and heavier before 1990 than they are today.

Currently, median lengths of Pacific hake are about 22 cm at Age 1, 34 cm at Age 2, 40 cm at Age 3, 42 cm at Age 4, 45 cm at Age 5, and 49 cm at Age 10. [2] Length distributions for 2009, 2011, and 2012 extend from about 15 or 20 cm to about 60 cm. All three distributions are bi-modal. In 2009 and 2011, there is a lower peak at about 22 cm and a higher peak at 39 cm in 2009 and at 40 cm in 2011. [2] In 2012, the higher peak is at 32 cm and the lower peak is at 40 cm. [4] The widths of the all the peaks are about 10 cm wide. However, the peaks for the longer fish have tails extending to about 60 cm.

Median lengths can be correlated to the 2013 estimations of abundance and juveniles shown in Figure 4. The 39 cm peak in 2009, when abundance was relatively low, can be attributed to Age 4 or Age 3 hake from the relatively weak 2005 and 2006 year classes. The 22 cm peak in 2009, the 39 cm peak in 2011, and the 40 cm peak in 2012, can be attributed to Age 1, Age 3, and Age 4, hake from the relatively strong 2009 year class. The 22 cm peak in 2011 and the 32 cm peak in 2012 can be attributed to Age 1 and Age 2 hake from the very strong 2010 year class. The tail of each distribution is produced by older hake. In 2009, there were still some Age 10 fish from the 1999 year class. In 2011 and 2012, the oldest fish of any significance were Age 6 and Age 7 fish from the 2005 year class. [8]

Recent hake assessments have used age-weight relationships rather than length-weight relationships for individual fish in their stock biomass modeling. [8] In 2009, the weights of Age 1, Age 4 and Age 10 fish were 70 gm, 470 gm, and 770 gm, respectively. In 2011, the weights of Age 1, Age 3 and Age 6 fish were 80 gm, 320 gm, and 600 gm, respectively. In 2012, the weights of Age 2, Age 4 and Age 7 fish were 210 gm, 410 gm, and 690 gm, respectively.

The most likely age/size distribution of hake during the summer of 2012 was a large percentage of Age 2 fish, 32 cm long, weighing 210 gm; a smaller percentage of Age 4 fish, 40 cm long, weighing 410 gm; and a few Age 7 fish, 46 cm long, weighing 690 gm.

SUMMERTIME GEOGRAPHIC DISTRIBUTIONS

Latitude

The primary goal of a fishery survey is to survey the complete stock, so that an accurate determination of stock size can be made. The geographic distribution of the stock is, at best, of secondary interest. Because the stocks of Pacific sardine and Pacific hake are moving during the summer, their geographic distributions will change throughout the summer. The 2012 NWASS and NMFS surveys present excellent pictures of the distributions of sardine and hake during the summer of 2012. It must be remembered that the surveys present a single snapshot of a dynamic situation. Actually, because the surveys take weeks to months to complete, the snapshot is more like time lapse photography where the camera and the subject are both moving; the camera moving much faster than the subject. Nevertheless, although the details of the distributions might change, the surveys provide an excellent overall picture of the latitudinal distribution of both sardine and hake.

Pacific Sardine

The photographic element of the 2012 NWASS survey was conducted from 31 July through 22 August. The NWASS philosophy is to fly opposite to the northward movement of sardines, so that none are double counted. The NMFS combined sardine/hake survey did both echo sounding and trawling throughout its 27 June through 23 August survey period. The NMFS survey began in the south and traveled north, under the assumption that the ships moved northward faster than the fish did.

Figure 5 shows the locations of sardine schools detected by NWASS during their 2009 through 2012 surveys. [3] In 2009, sardines were concentrated between about 45.5°N and 47.5°N. In 2010 and 2011 they extended from about 45.5°N to above 48°N. In 2012 they were concentrated between about 44.5°N and 47°N, with some extending south to almost 43°N. The 2012 distribution was significantly farther south than the previous years, especially 2010 and 2011.

Figure 6 shows the distribution of Pacific sardine biomass determined by the 2012 NMFS survey. [5] The heaviest concentrations of sardines were from north of San Francisco (38°N) to Cape

Mendocino (40°N). There were continuous light concentrations from Cape Mendocino to south of Cape Blanco (42.5°) and a few sardines between 42.5°N and 43.5°N. Sardines were heavily concentrated from about 43.5°N to north of Newport, OR (45°N). There were a few sardines along the Washington coast (46°N to 48°N).

The NRL experiment area extended from about 42.9°N to 46.75°N. In 2012, NWASS found concentrations of sardine schools on every transect from 46.75°N to 44.5°N, except for two transects at 45.12°N and 45.25°N. Schools were sporadic between 44.5°N and 42.9°N, the southern limit of the experiment area. Thus, NWASS found sardines primarily in the northern 60% of the experiment area. Conversely, the NMFS survey found sardines primarily in the southern 55% of the experiment area, south of 45°N. The only area of overlap was off Newport, between 44.5°N and 45°N.

NMFS surveyed between San Francisco, CA and Newport, OR from July 16 to 26. It then surveyed between Newport and Port Angeles, WA from July 30 to August 12. NWASS surveyed off Washington from July 31 to August 19 and off Oregon from August 19 to 22. Weather conditions, primarily fog, forced NWASS to spend almost three weeks to complete the aircraft transects off Washington. Good weather allowed them to complete the transects off Oregon in four days. NMFS surveyed the NRL experiment area two to three weeks before NWASS did. It is quite possible that a northward migration of sardines occurred during this time period. If so, that could explain the difference in the distribution of sardines seen by the two surveys within NRL experiment area.

The New Horizon had a scientific echo sounder aboard during the NRL experiment, operating at 18 and 38 kHz. It was run continuously, but not systematically, during the experiment. A systematic echo sounder survey would have tracks covering the latitudinal range of the experiment area and extending from shallow to deep water (as did the NMFS survey) both day and night. During the NRL experiment, echo sounding was dictated by the NRL acoustic clutter measurements, which meant that, during much of the experiment, the New Horizon was sailing within a relatively small area in water depths greater than 200 m. However, there were several opportunities to echo sound in waters shallower than 200 m.

Groups of near surface targets were detected by the New Horizon echo sounder at night near 43.5°N, 44.5°N, 45°N, and 46°N. Figure 7 shows the 30 minute 38 kHz echo sounder record that contained the highest concentration of such targets. (The standard fisheries sonar frequency has been 38 kHz for decades.) It is impossible to positively identify a biological target with acoustics only, which is why NMFS conducts combined echo sounder/trawl surveys.

However, given the nature of the targets and their depth (to be discussed later) and the relative abundance of sardine compared to other near-surface species, it is unlikely that the targets were anything but sardines. Therefore, it has been assumed that the targets were, in fact, sardines. The range of latitudes over which sardines were seen practically spans the NRL experiment area. In addition, the northernmost sardines were encountered on July 29 and the southernmost on August 5. Thus, it is reasonable to presume that sardines were at experimental latitudes throughout the experiment and that they did not migrate north out of the area during the experiment.

The echo sounder on the Oceanus periodically saw small near-surface schools during the day. The schools dispersed at night. The fish were not identified but sardines were seen at the surface at night when the schools dispersed, so it is assumed that the schools were most likely sardines. [6]

Catches of Pacific sardine off Oregon and Washington (and British Columbia) are made almost entirely in the second half of the year, primarily in the summer and early fall. [12] Figure 3c shows that 2012 catches off these states were quite high compared to those off California and British Columbia, with the catch off Oregon about 20% higher than the catch off Washington. Hence, these statistics imply that sardines were abundant in the NRL experiment area during the summer of 2012.

Pacific Hake

Figure 8 shows the locations of Pacific hake detected by NMFS during its 2007 through 2012 surveys. [4] In all four surveys hake were found all along the coast of the United States from Monterrey Bay to Port Angeles. There were year-to-year differences in distribution. There were significantly more hake south of 40°N and the distribution was less uniform in 2012 than in the other years. There were more hake north of 40°N in 2007 and 2009 than in 2011 and 2012.

The year-to-year differences in hake distributions along the U.S. coast are small compared to those off British Columbia. In 2007, there were large numbers of hake north of Vancouver Island. In 2011, there were very few hake anywhere. In 2007, there were still some hake of the 1999 year class migrating far north. In 2009, there were only a few of these fish left and by 2011, there were very few.

In 2012, NMFS ran 25 echo sounder transects between 42.5°N and 47°N. Hake were detected on every one of these transects. Thus, the NMFS survey detected hake on each transect within the NRL experiment area. Heaviest concentrations of hake within this area were between 44.8°N to 45.7°N.

The Oceanus consistently detected hake in mid-water and near the bottom during the OSU/NWFSC experiment. Age 2 and Age 3 hake were found in the same locations but at different depths. Layers of zooplankton were also common. [6]

The New Horizon detected a number of mid-water targets, typically while NRL was conducting acoustic measurements in waters deeper than 200 m. Consultation with experts from OSU and NWFSC indicated that some, but not all, of these targets were probably hake. [6, 18] Figure 9 shows two 30 minute 38 kHz echo sounder records containing targets that were deemed most likely to be hake.

As noted above, the shore-based catches of hake shown in Figure 4c do not provide a complete picture of abundance, due to the large numbers of hake that are caught and processed at sea. However, the fact that 2012 shore-based catches off Oregon were significantly higher than off Washington matches the distribution of hake shown in Figure 8, where hake were found to be much more abundant off Oregon than off Washington.

Bottom Depths and Distances from Shore

Pacific Sardine

Coastal pelagic species, such as Pacific sardine, are, as the name implies, are often near the coast, on the continental shelf. They are also generally well above the bottom. As such, actual bottom depth is not a large driving factor in their distribution. It appears that distance from shore is a bigger driver. If ocean features, such as canyons, extend toward shore, sardines may well be found over deep water.

The 2012 NWASS survey found sardines from about 3 nm from shore, near the eastern end of the transects, to 31 nm offshore, near the western end of the transects. [3] Average near shore and offshore distances for the 23 transects on which sardines were seen were about 9 nm and 20 nm, respectively. Sardines were closer to shore off northern Oregon (between 44.9°N and 45.75°N) and than they were off Washington and central and southern Oregon. Off northern Oregon, average near shore and offshore distances were about 6 nm and 14 nm, respectively. This area was the only one where near shore distances of 3 nm were seen. In the other two areas, average near shore and offshore distances were about 11 nm and 25 nm, respectively. Relative to the NRL experiment, NWASS saw sardine closer to shore in the northern half of the experimental area (north of 44.9°N) and farther from shore in the southern half (south of 44.9°N).

NWASS captured sardine schools off southern Washington (between 46.5°N and 46.8°N) and northern Oregon (between 45.9°N and 46.2°N). Distances off shore of Washington ranged from 14 to 21 nm. Distances off shore of Oregon ranged from 8 to 24 nm. As Figure 5 shows, catches off Oregon were within the offshore range where sardines were photographed, while several catches off Washington were inshore of that range. The school capture portion of the survey began the day after the aerial portion of the survey ended. It appears that sardines moved a few miles shoreward during the period between the aerial photography and capture portions of the survey.

Bottom depths over which NWASS found sardines at the near shore ends of the transects were between 50 and 130 m, with the exception of one outlier at 400 m. The outlier occurred on the southernmost transect, where sardines were sparse. Excluding the outlier, the mean near shore depth was 85 m. Near shore bottom depths averaged 75 m off northern Oregon and 90 m off Washington and central and southern Oregon.

Bottom depths over which NWASS found sardines at the offshore ends of the transects were between 100 and almost 900 m. The mean offshore depth was 280 m and the median was 180 m. Offshore bottom depths averaged 140 m off northern Oregon and 290 m off Washington and central and southern Oregon.

NWASS captured sardine schools off Oregon over bottom depths of 65 to 135 m. Off Washington, depths were limited to 70 to 100 m.

The echo sounder on the New Horizon encountered sardines from 7 to 28 nm offshore over bottom depths from 85 to 300 m. In the northern part of the NRL experiment area (about 45°N and 46°N), sardines were found between 7 and 15 nm offshore over bottom depths of 85 to 150 m. In the central part of the area (44.5°N), sardines were found between 23 and 28 nm offshore over bottom depths of 200 to 300 m. In the southern part of the area (43.5°N), sardines were found at 15 nm offshore over a bottom depth of 190 m. All of the sardine schools observed on the New Horizon echo sounder were within the offshore distances where NWASS saw sardines.

Pacific Hake

The echo sounder on the Shimada found hake at about 10 to 35 nm from shore in the NRL experiment area. [4] Near shore distances ranged from about 10 to 30 nm and offshore distances ranged from about 20 to 35 nm. The NRL clutter measurement boxes shown in Figure 1 extend from about 7 to 40 nm from shore. Thus, the NRL measurements extended from slightly inshore to slightly offshore of where the NMFS survey saw hake.

Bottom depths over which hake were found ranged from 100 to 1000 m for the complete NMFS survey. Only small percentages of hake were in waters less than 200 m or greater than 800 m, most were between 300 and 600 m and the mode was at about 400 m. [17]

The OSU/NWFSC experiment consistently saw hake over bottom depths between 200 and 450 m within the NRL experiment site. [6] The New Horizon saw hake-like targets only over bottoms that were greater than 200 m, never shallower.

SUMMERTIME DEPTH DISTRIBUTIONS

Pacific Sardine

In the past, SWFSC surveyed Pacific sardine only when they were spawning off California during the spring. During spawning, sardines school in the upper 50 m or so during the day and rise to near the surface and disperse at night. Thus, during their surveys, SWFSC assures that their acoustic system and trawls include the deepest depth they expect to find sardines: 70 m. [19] This scenario has often been presented as if it were true throughout the year. However, it does not hold for the summer, when sardines are feeding off the coast of the Pacific Northwest. It is very unlikely that aerial photographs could provide an accurate assessment of the sardine stock if the fish were as deep as 50 m. However, the fish are much shallower than 50 m and aerial photography is successful.

The NWASS methodology determines abundance of sardines within a school per square meter. Thus, it very accurately measures the surface area of schools and weighs those schools that it catches to calibrate school area versus weight. As an incidental part of the school capture process, the fishing boats use high frequency sonars to determine the approximate top and bottom of each school. [3, 20-22] (A small number of schools were captured in 2012. Therefore, data obtained from the captured schools includes 2009 through 2012.) The tops of the schools ranged from near the surface to 9 m, with a mean of about 4 m. The bottoms ranged from 4 to 22 m, with a mean of about 10 m.

The New Horizon echo sounder found sardine-like targets during several nights. The targets were in the upper 10 to 30 m over bottom depths ranging from 80 to 300 m.

Pacific Hake

Just as bottom depth is not a driving factor for near surface species, such as Pacific sardine, distance from the surface is not a driving factor for semi-demersal fish, such as Pacific hake.

Nevertheless, it is of interest and is collected as a fundamental component of echo sounding.

Shimada echo sounder records from transects south of the NRL experiment area (36°N to 42°N) provide a picture of hake depth versus bottom depth. [17] There is no reason to expect significant changes in hake depth behavior north of 42°N, so these records are assumed to be valid for the NRL experiment area. The records cover bottom depths of about 150 m to 500 m, as the Shimada traversed the shelf break. These bottom depths virtually match those in which the NRL measurements were made.

The Shimada records show that, during the day in areas where the bottom is relatively flat, variations in hake depth were relatively small. However, in different areas where bottom depths were similar, hake may have been at different depths. In areas where the bottom was between 175 m and 300 m, hake aggregations were between 120 and 220 m deep, with most between 150 and 200 m. The aggregations were 10 to 30 m thick but their depths often slowly varied over 40 to 50 m. The aggregations were 20 to 130 m above the bottom, with most between 50 and 100 m above.

In areas where the bottom was sloping, between 300 and 500 m, hake depths tended to remain constant. The aggregations were between 125 and 300 m deep, with most between 200 and 250 m. The aggregations were 10 to 40 m thick but their depths often slowly varied over 40 m to 80 m. The aggregations were 100 to 200 m above the bottom.

Although the NMFS survey plan called for echo sounding during the day, data were sometimes obtained at night. A transect at 40°N over bottom depths of 240 to 360 m showed hake between 60 and 160 m deep, independent of bottom depth. The aggregations were 20 to 40 m thick.

During the day in 200 m, the Oceanus echo sounder found hake from just above the bottom to 25 to 50 m above bottom. During the day in 400 m of water, there was a layer of hake about 25 m thick about 25 m above the bottom and another layer 10 to 20 m thick 100 to 150 m above the bottom. At night, hake were dispersed throughout much of the lower half of the water column. [6]

During the day, the New Horizon echo sounder found hake-like targets over bottom depths between 200 and 300 m. Over bottom depths between 200 and 250 m, targets were between 100 and 200 m deep, with most between 140 and 180 m. They were 40 to 80 m above the bottom, with most between 50 and 70 m above. Over bottom depths between 250 and 300 m, targets were between 130 and 240 m deep, with most between 160 and 210 m. They were 60 to 100 m above the bottom, with most between 70 and 90 m above. The targets were generally 10 to 30 m thick over the 200 to 300 m bottom depth range.

At night the New Horizon found hake-like targets over bottom depths between 220 and 240 m. The targets were at depths between 80 and 120 m, about 110 to 140 above the bottom. The targets were more diffuse than those seen during the day and were 20 to 40 m thick.

At one daytime location, over bottom depths of 400 to 500 m, the New Horizon found a continuous layer, which was unlike the targets seen in shallower water. The layer was 10 to 20 m thick at a depth of about 300 m. It extended for over 10 nm as the New Horizon sailed south-southwesterly along the slope. NMFS saw similar layers, composed of Age 2 hake over much of its survey. [18] Therefore, it is assumed that this layer seen by the New Horizon was made up of Age 2 hake.

AGGREGATIONAL CHARACTERISTICS

Pacific Sardine

Equivalent circular diameters of daytime sardine schools have been calculated from the school areas measured from the NWASS aerial photographs. [3] As shown in Figure 10, diameters ranged from less than 10 m to over 100 m. The mode of the distribution is 20 m, and the mean is 29 m. Examination of several hundred photographs indicated that the smallest schools were essentially circular in the horizontal plane. Many intermediate schools had parallel sides, which were either straight or curved, and round ends. Not surprisingly, the largest schools often had irregular shapes. Length-to-width ratios of the schools increased with increasing diameter. Schools with diameters of 30 to 40 m had average ratios of about 2, while schools with diameters or 80 m or more had average ratios of about 3.

School thicknesses of the captured schools varied little with school diameter. [3] School thicknesses were between 2 and 18 m, with a mean of 6 m.

Most of the sardines seen by the New Horizon echo sounder during the night had horizontal dimensions of 30 to 50 m. Some were 100 to 200 m wide and one was more than 500 m. The targets were 5 to 15 m thick.

Since NWASS measures both the weight of its captured schools and the mean weight of a sample of individual fish, the number of fish in each school can be determined. However, NWASS does not try to capture very large schools, so the numbers of sardines in such schools must be estimated. Although school areas and heights are measured, school shapes must be determined before school volumes can be calculated. Aerial photographs show that the larger schools are generally uniformly bright with duller edges, indicating that they are essentially flat on top with rounded edges. [23] A reasonable approximation of the smallest schools is that they are circular with flat tops and bottoms and rounded edges – they resemble a wheel of cheese. Conceptually, larger schools can be thought of as a larger wheel of cheese that is sliced in half, the two halves separated, and the space between the halves filled with material that has the same cross-section as the wheel. The halves could be separated in a straight of curved line, but, for simplicity, it is assumed that all larger schools have straight sides and rounded ends. Thus, if a school were sliced in any of the three perpendicular planes through its center, the cross-sections of each would look like a race track.

Given the assumed shapes, sardine school densities can be estimated. Densities in terms of fish per body length cubed ($\#/L^3$) ranged from about $0.13/L^3$ to $1.5/L^3$. For a 23 cm sardine, a density of $1.0/L^3$ equates to $82/m^3$. Table 1 shows the estimated density distributions for different school sizes. Only the smallest schools have the highest density and only the largest schools have the lowest density. Combining the school size distribution from Figure 10 with the density distributions in Table 1 produces the size-density distribution in terms of numbers of schools shown in Table 2

The numbers of sardines in the schools can then be calculated for different combinations of school volume and density. The results are shown in Table 3a. The least dense small school contains about 5000 fish and the larger schools have about one million fish. Table 3b shows the calculated weights of the schools for a mean sardine weight of 150 gm. Weights range from less than 1 to 168 mt.

Multiplying the values in Table 2 by the corresponding values in Table 3b and summing the results gives a total weight of 10,000 sardine schools of 246,934 mt. The official estimate of the size of the sardine stock for July 2012 was 659,539 MT. [7] Hence, based on calculations using the NWASS data, the estimated total number of sardine schools off the west coast of the United States during the NRL experiment period was about 26,700. Table 4 shows that, of these, 23,600 had equivalent circular diameters of 40 m or less, 2600 had diameters of 50 to 70 m, and 500 had diameters of 80 m or more.

The area over which sardines were seen by NWASS was about 5000 km^2. If the schools were uniformly distributed over that area, there would about $5/km^2$, with one very large school every 5 km^2. But the schools are not uniformly distributed. The very few aerial photographs that were examined for school shapes, out of thousands that were taken, can give some indication of the range of areal densities during the summer of 2012. The photographs cover approximately 2.25 km^2. About 10% of the photographs examined had no schools, 50% had between 1 and 4 schools, and 6% had about 20 schools. This small sample indicates that, where sardine schools are present during the day, there will be between about 0.5 and 2/km^2 over half the area, while about 5% of the area could have 10/km^2

Pacific Hake

The data on aggregations of Pacific hake are not nearly as comprehensive as that for Pacific sardine. The data come almost solely from echo sounder records and, given the NMFS hake survey methodology, almost all of it is from the daytime. In addition, NMFS seems to refer to both hake layers and hake schools without clearly defining the difference.

Echo sounders provide excellent data on the thickness of daytime hake aggregations. As noted above, echo sounders used during summer 2012 found the aggregations to be 10 to 40 m thick over bottom depths in which the NRL experiment took place. In deeper water, up to 1500 m, the Shimada found a few aggregations to be between 200 and 250 m thick. [17]

Determining the horizontal dimensions of hake aggregations from echo sounder records is subject to interpretation. The picture on an echo sounder display depends on ship speed and on the echo sounder settings. Figure 9 shows New Horizon records of targets that are most likely hake. In Figure 9a, the ship speed was about 3.5 kt, and the record shows 10 patches of scattering, about 100 to 300 m wide, separated by distances of 50 to 200 m. (The double line passing through the record is the second bottom reflection.) In contrast, in Figure 9b, the ship speed was about 10.5 kt. The hake in center of the record appear to be in a continuous wavy line. (The ship did not cross a ridge. Unfortunately, it reached a turning point shortly after encountering the hake.) The picture in Figure 9b looks much more like those obtained by NWFSC, whose hake surveys are conducted at 10 kt, than do the typical New Horizon records, such as Figure 9a, which were obtained primarily at 3 to 4 kt.

Binned Shimada data from summer 2012, indicates that most hake "school" lengths are in the 5 nm bin. [17] However, a few "schools" are in the 55 nm bin. "Schools" of these lengths definitely can not be "schools" in the strict sense, where a school is defined as a group of fish of similar size swimming in concert in the same direction. Long, thin aggregations of fish are more properly called layers. In fact, the data set that contains the hake school lengths also includes data on hake layer depths.

Broad band low frequency measurements of scattering from layers of hake in deep water found that hake density in these layers is very low. Densities were less than 2 x $10^{-4}/m^3$. [24] It is reasonable to assume that density is not significantly higher in shallower water.

Based on the echo sounder data obtained by the Shimada and the New Horizon, it seems as though the most proper way to consider daytime hake aggregations in the horizontal is as extended wavy layers with regions of higher and lower intensity.

SCATTERING

At low frequencies, scattering from a swimbladder-bearing fish is completely dominated by scattering from the swimbladder. At a certain frequency, which is a function of swimbladder size and fish depth, the swimbladder will resonate. Scattering in this region is uniform in all directions. A theoretical model is available to estimate the scattering from a single swimbladder-bearing fish near resonance. [25]

At higher frequencies, in the geometric scattering region where fish length (L) is equal to or greater than the acoustic wavelength (λ), the swimbladder is still a major component of the scattering. However, scattering from it becomes directional. Also, interferences caused by scattering from different parts of the fish body or by the shape of the swimbladder itself cause the magnitude of the scattering to vary with frequency and fish aspect.

Even though scattering can vary rapidly with frequency in the geometric region for a single fish, small differences among fish of the same species tend to average out these variations for a group of fish. Therefore, scattering in this region can be considered to be independent of frequency. A set of empirical equations is available to predict scattering from a single fish in the geometric region. [26]

Pacific Sardine

Figure 11 shows the target strength of a single adult Pacific sardine, 23 cm long, at a depth of 7 m. The swimbladder resonance frequency is about 400 Hz. The target strength at the peak is -25 dB. Above resonance, the target strength drops to about -39 dB. In the geometric region, the target strength of the fish at side aspect is -36 dB. At head and tail aspects, it is about -49 dB and -51 db, respectively. Intermediate aspects have target strengths between those of the side and head and tail.

If the sardines in a school were far enough apart that there were no acoustic interactions among them, the target strengths of the individuals would add incoherently. If that were so, a school of one million identical fish would have a target strength of +35 dB at 400 Hz and a target strength of +24 dB at side aspect in the geometric region.

However, the sardines in a school are quite close together and acoustic interactions, such as multiple scattering and attenuation, can occur. Thus, the target strength of a sardine school should be significantly lower than these values. [27, 28] This subject is currently under investigation.

Pacific Hake

Figure 12a shows the target strength of a single adult Pacific hake, 40 cm long, at a depth of 150 m. The swimbladder resonance frequency of the adult is about 1000 Hz. The target strength at the peak is -20 dB. Above resonance, the target strength drops to about -37 dB. In the geometric region, the target strength of the fish at side aspect is -31 dB. At head and tail aspects, it is about -44 dB and -46 db, respectively. Intermediate aspects have target strengths between those of the side and head and tail.

Figure 12b shows the target strength of a single Age 2 hake, 32 cm long at a depth of 300 m. The swimbladder resonance frequency of the adult is about 2140 Hz. The target strength at the peak is about -25 dB. In the geometric region, the target strength of the fish at side aspect is -33 dB. At head and tail aspects, it is about -46 dB and -48 db, respectively. Intermediate aspects have target strengths between those of the side and head and tail.

Individual hake are far enough apart that the there are no acoustic interactions among them. [24] Thus, if the resonance peak in the low frequency curve in Figure 12 were spread to account for variations in fish size and depth, the result would resemble what would be obtained when scattering from a layer of hake.

SUMMARY

In the summer of 2012, NRL conducted an experiment off the coasts of Oregon and Washington to investigate acoustic clutter caused by aggregations of fish. Fortunately, one experiment and two surveys that were focused on the fish themselves were also conducted in the experiment area at about the same time. These provide much valuable information on Pacific sardine and Pacific hake, which, prior to the experiment, were assumed to be the two most abundant species in the experiment area and which, therefore, were assumed to be the most likely species to produce clutter.

The surveys showed that both sardines and hake were abundant at the latitudes of the NRL experiment area. Average near shore and offshore distances where sardines were found were 9 and 20 nm. Average near shore and offshore bottom depths over which they were found were 85 and 280 m. Hake were found between 10 and 35 nm from shore. Very few were found over bottom depths less than 200 m; most were between 300 and 600 m.

The mean length of Pacific sardines was 23 cm. During the day, sardines were in shallow schools. The mean depths of the tops and bottoms of the schools were 4 and 10 m. Equivalent circular diameters of these schools ranged from under 10 m to over 100 m. The mean school diameter was 29 m. At night the schools dispersed in the upper 30 m.

Two age groups of Pacific hake had mean lengths of 32 and 40 cm. During the day, hake were often in wavy layers that had patches of varying intensity. The layers were 10 to 40 m thick and extended for miles. Daytime depths of hake in the NRL experiment area were generally between 150 and 200 m. At night the hake dispersed vertically but their mean depth did not change significantly.

A single adult sardine at its average daytime depth of 7 m has a swimbladder resonance frequency of about 400 Hz. Its target strength at that frequency is -25 dB. At higher frequencies, in the geometric scattering region, its side-aspect target strength is about -36 dB.

A single adult (40 cm) hake at a depth of 150 m has a swimbladder resonance frequency of about 1000 Hz. Its target strength at that frequency is -20 dB. At higher frequencies, in the geometric scattering region, its side-aspect target strength is about -31 dB.

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Table 1 – Estimated density distributions of different sardine school sizes

Equivalent School Diameter	Density - Fish/L^3						
m	0.13	0.19	0.29	0.41	0.59	0.91	1.50
10-30	0	0.08	0.15	0.18	0.21	0.27	0.11
40	0	0.09	0.19	0.25	0.29	0.18	0
50-60	0	0.20	0.27	0.33	0.20	0	0
70	0	0.27	0.35	0.25	0.13	0	0
80-90	0.30	0.40	0.30	0	0	0	0
100-110	0.50	0.50	0	0	0	0	0

Table 2 – Estimated sardine school size-density distribution for 10,000 schools

Equivalent School Diameter	Number of Schools Density - Fish/L^3						
m	0.13	0.19	0.29	0.41	0.59	0.91	1.50
10		107	201	242	281	362	147
20		320	600	720	840	1080	440
30		189	354	425	495	637	260
40		104	218	287	334	207	
50		108	146	178	108		
60		52	70	86	52		
70		46	60	42	22		
80	21	28	21				
90	18	24	18				
100	15	15					
110	10	10					

Table 3a – Estimated numbers of sardines in a school as a function of school size and density

Equivalent School Diameter	Numbers of Fish Density - Fish/L^3						
m	0.13	0.19	0.29	0.41	0.59	0.91	1.50
10		4909	7624	10626	15483	23759	39242
20		22577	35067	48877	71214	109283	180497
30		54579	84772	118158	172156	264186	436342
40		102358	158981	221593	322862	495455	
50		167356	259936	362309	527884		
60		251018	389879	543427	791775		
70		354786	551051	768075	1119087		
80	326880	480104	745694				
90	427857	628415	976049				
100	545472	801163					
110	680708	999790					

Table 3b – Estimated weights of sardine schools as a function of school size and density

Equivalent School Diameter	Weights of Schools - mt Density - Fish/L3						
m	0.13	0.19	0.29	0.41	0.59	0.91	1.50
10		0.7	1.1	1.6	2.3	3.6	5.9
20		3.4	5.3	7.3	10.7	16.4	27.1
30		8.2	12.7	17.7	25.8	39.6	65.5
40		15.4	23.8	33.2	48.4	74.3	
50		25.1	39.0	54.3	79.2		
60		37.7	58.5	81.5	118.8		
70		53.2	82.7	115.2	167.9		
80	49.0	72.0	111.9				
90	64.2	94.3	146.4				
100	81.8	120.2					
110	102.1	150.0					

Table 4 – Estimated numbers of sardine schools of different sizes and densities in 2012.

Equivalent School Diameter	Number of Schools Density - Fish/L3						
m	0.13	0.19	0.29	0.41	0.59	0.91	1.50
10		286	537	646	750	967	392
20		854	1602	1922	2243	2884	1175
30		505	945	1135	1322	1701	694
40		278	582	766	892	553	
50		288	390	475	288		
60		139	187	230	139		
70		123	160	112	59		
80	56	75	56				
90	48	64	48				
100	40	40					
110	27	27					

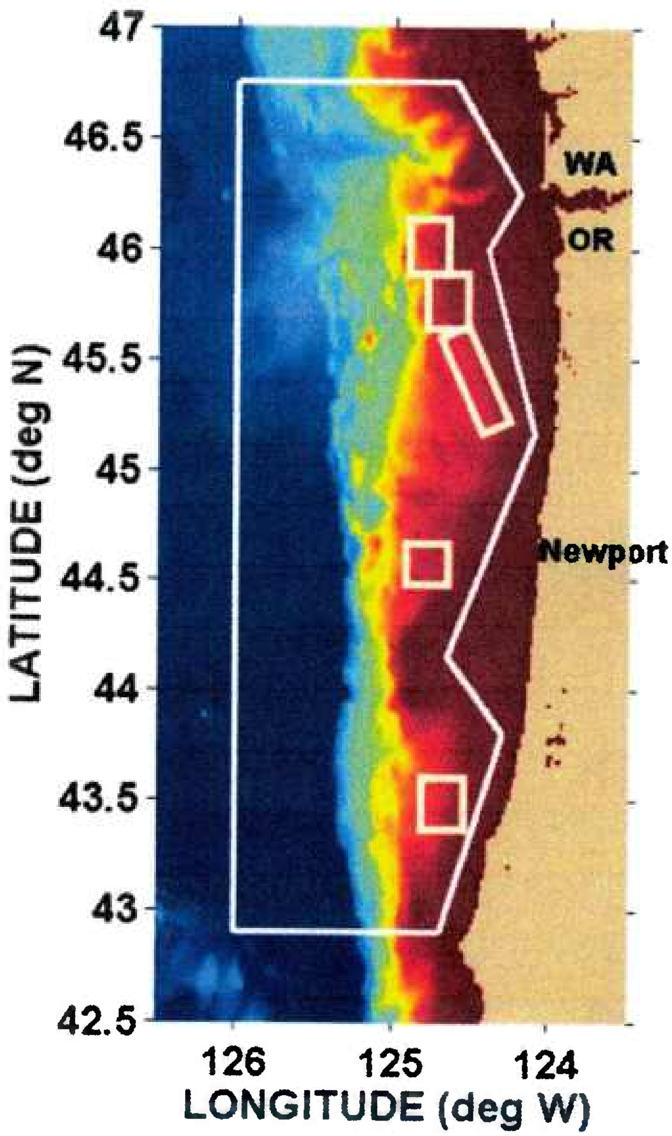


Figure 1 – NRL experiment area

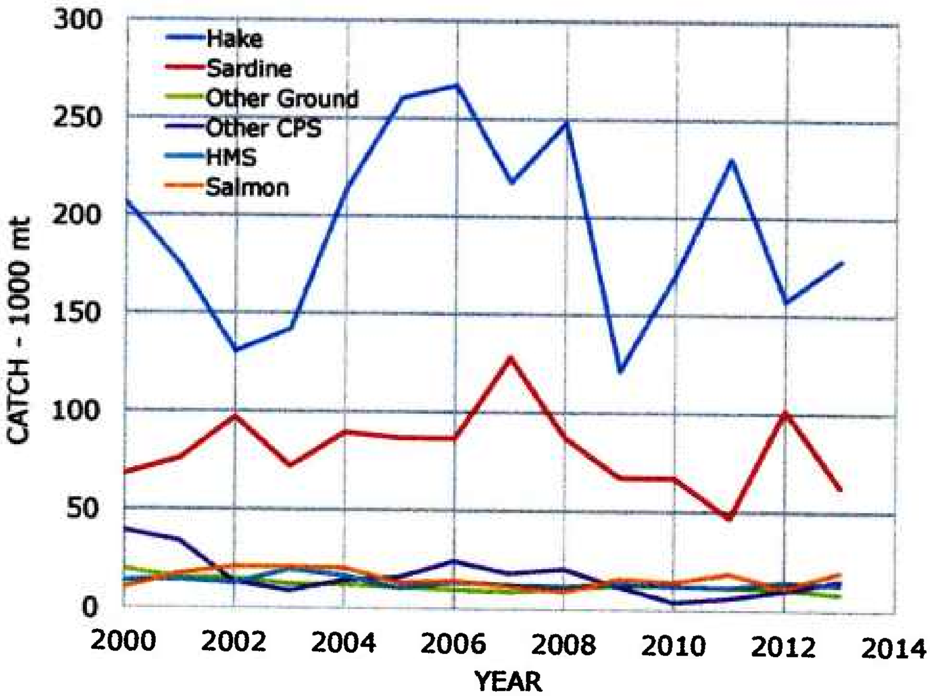


Figure 2 - Fish catches off the U. S. West Coast

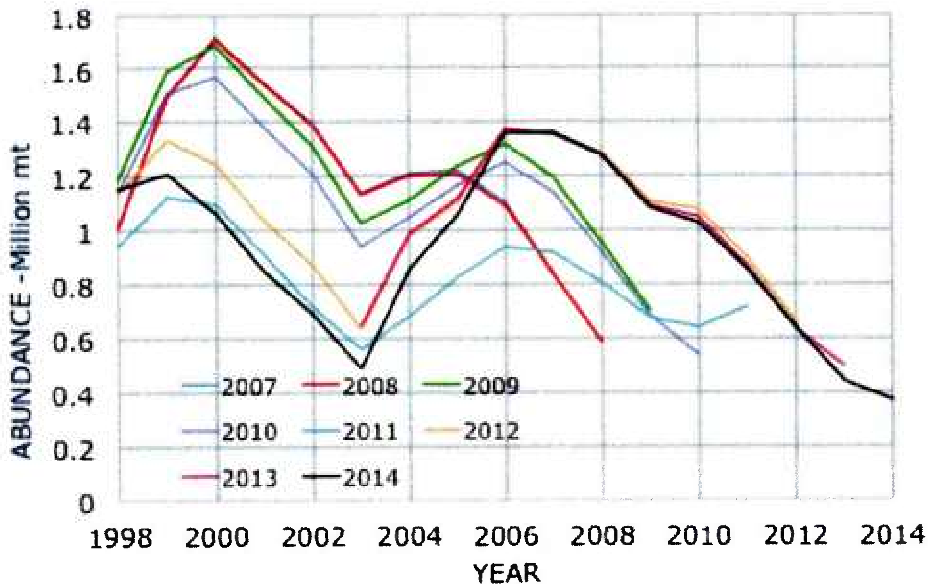


Figure 3a - Estimations of Pacific sardine abundance

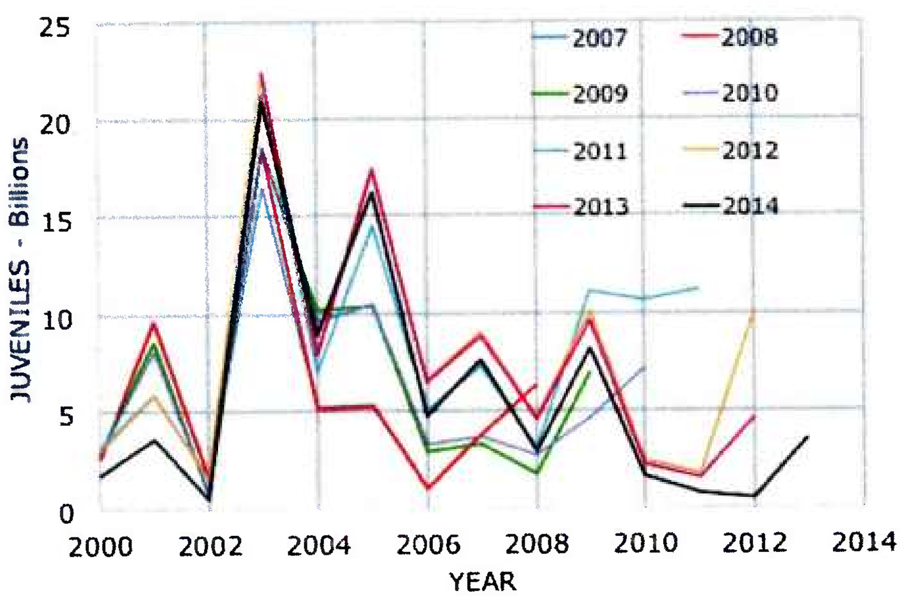


Figure 3b - Estimated numbers of Pacific sardine juveniles

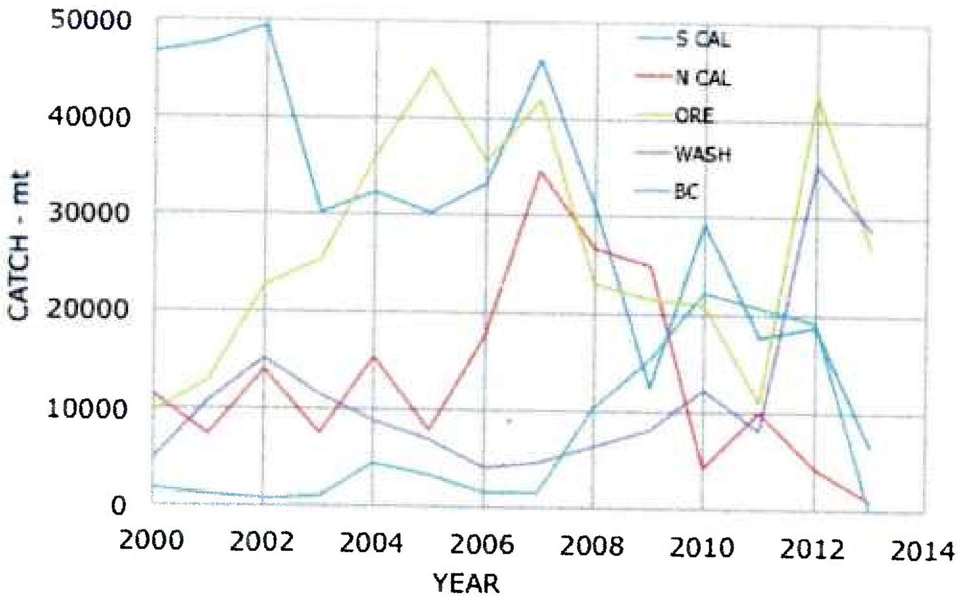


Figure 3c - Pacific sardine catches by region

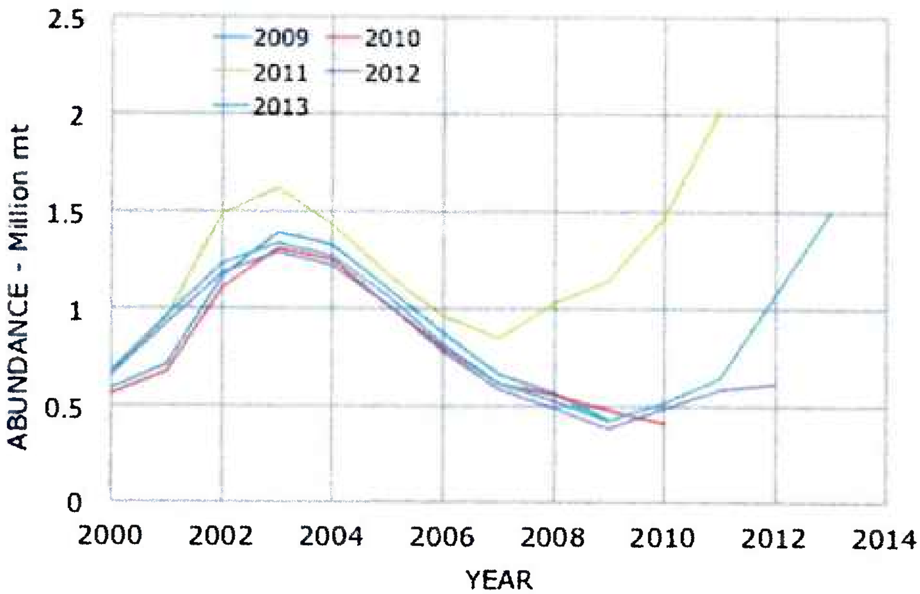


Figure 4a - Estimations of Pacific hake spawning female abundance

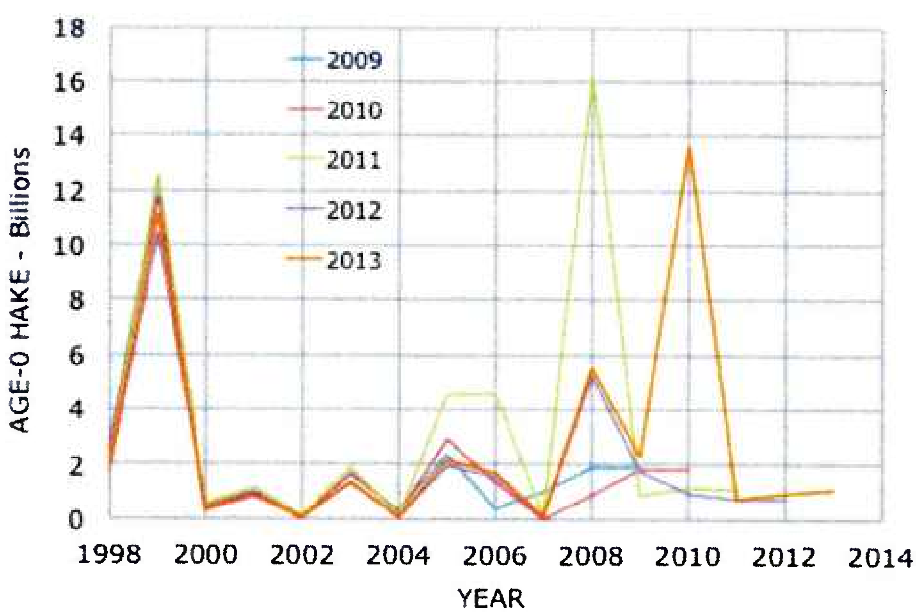


Figure 4b - Estimated numbers of Age-0 Pacific hake

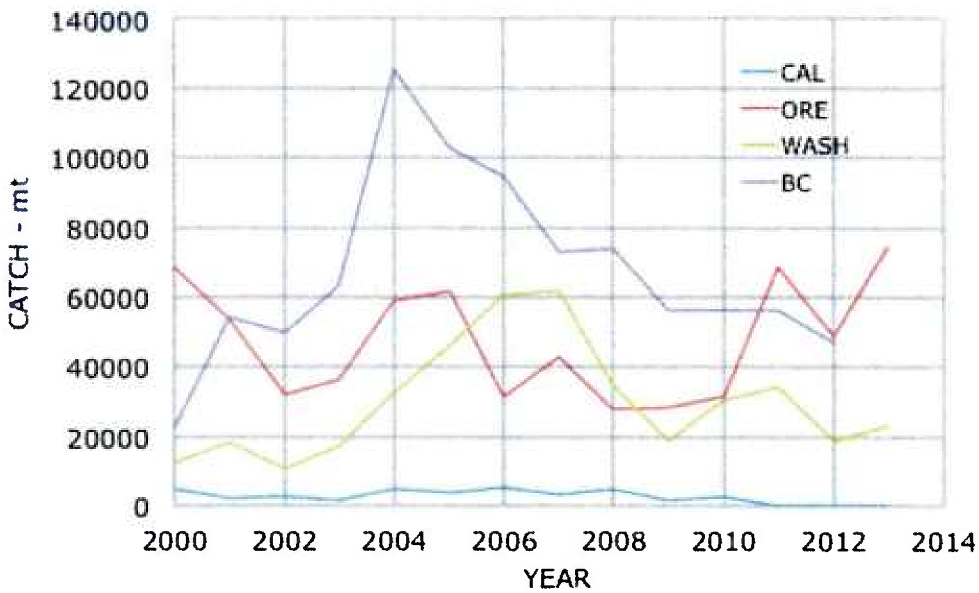


Figure 4c - Pacific hake catches landed ashore by region

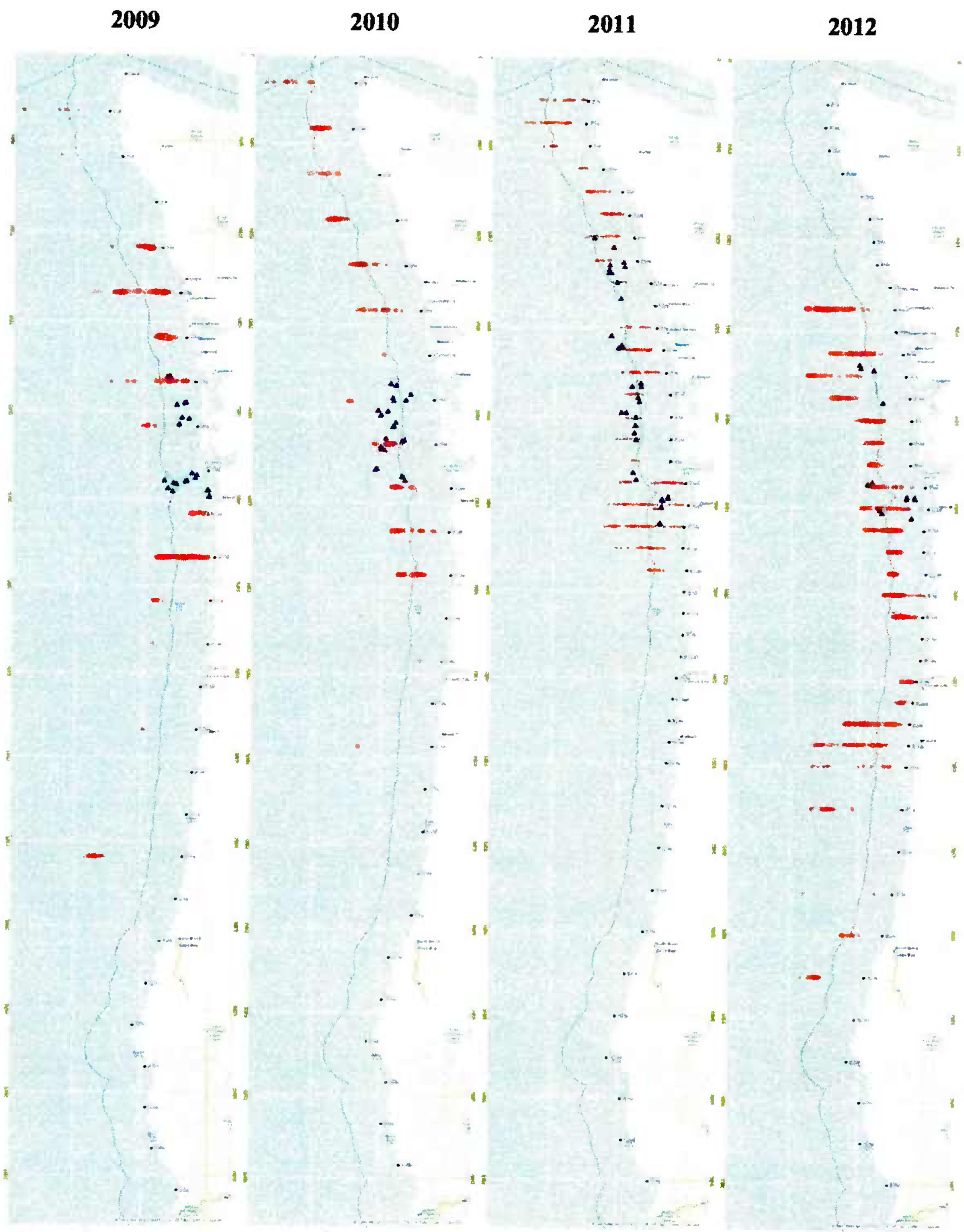


Figure 5 – Summertime geographic distributions of Pacific sardines, as determined by NWASS. Orange dots are school locations. Blue dots are locations of school captures. (Reprinted with permission of NWASS)

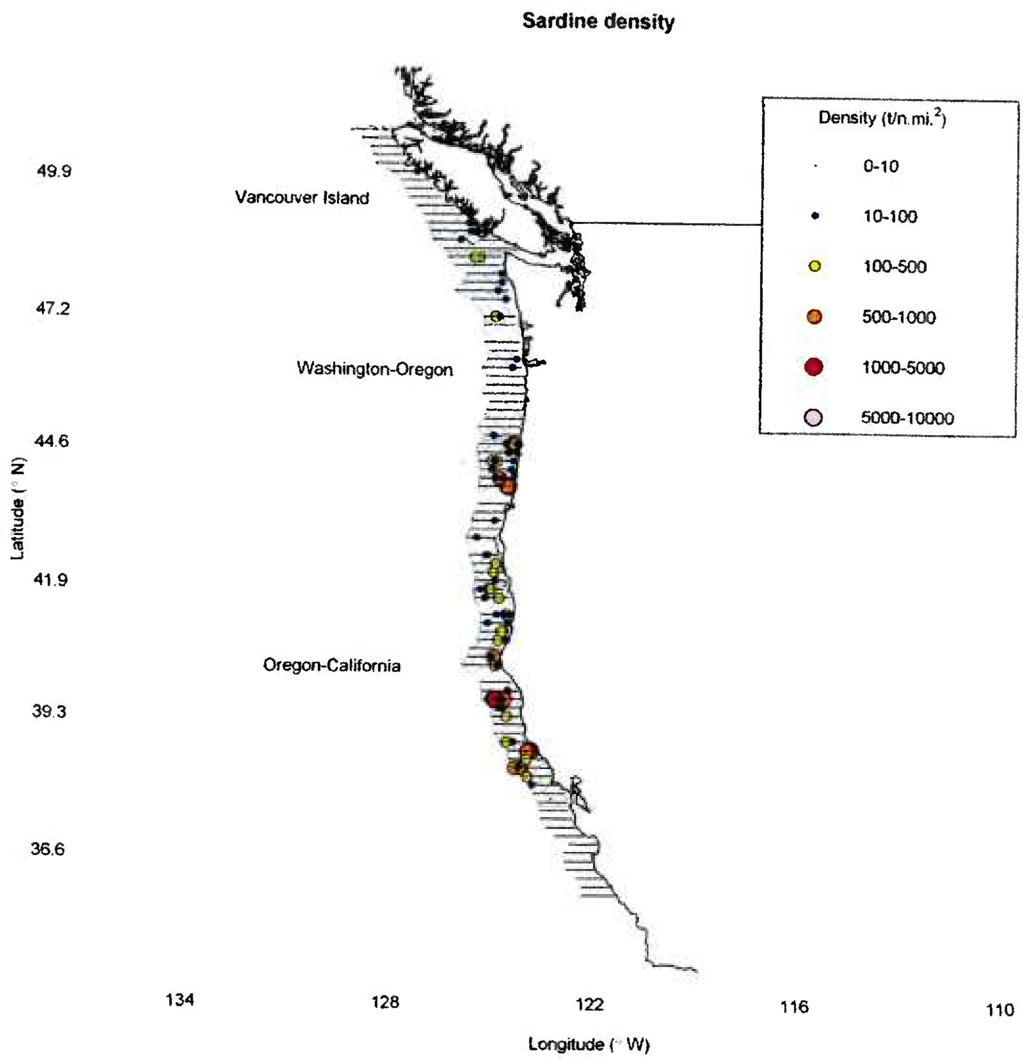


Figure 6 – Summertime geographic distributions of Pacific sardines, as determined by NMFS/SWFSC. (Reprinted with permission of NMFS/SWFSC)

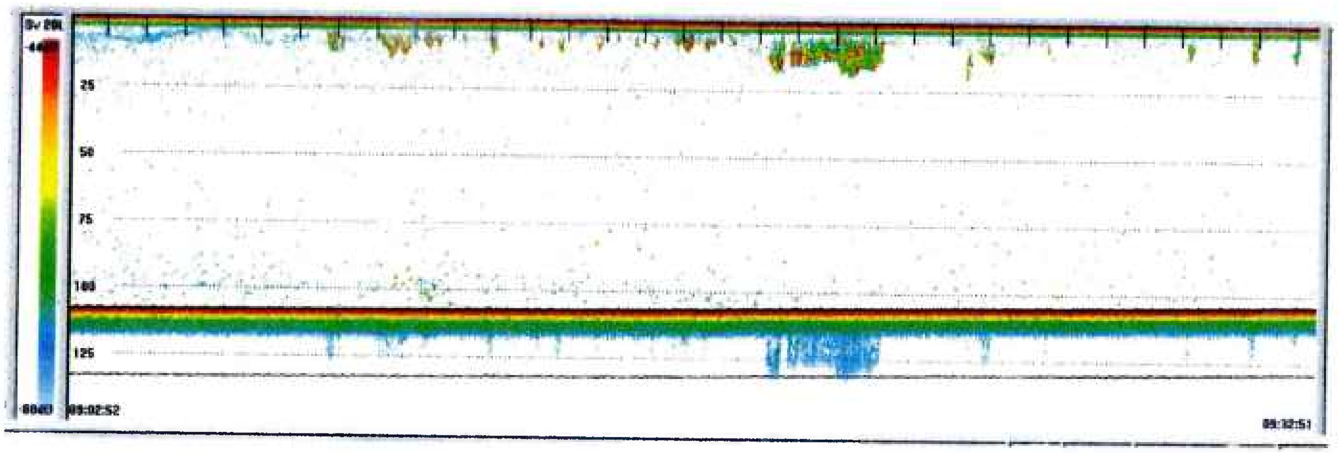


Figure 7 – New Horizon nighttime 38 kHz echo sounder record showing high concentrations of sardine-like targets. Ship speed was 7 kt.

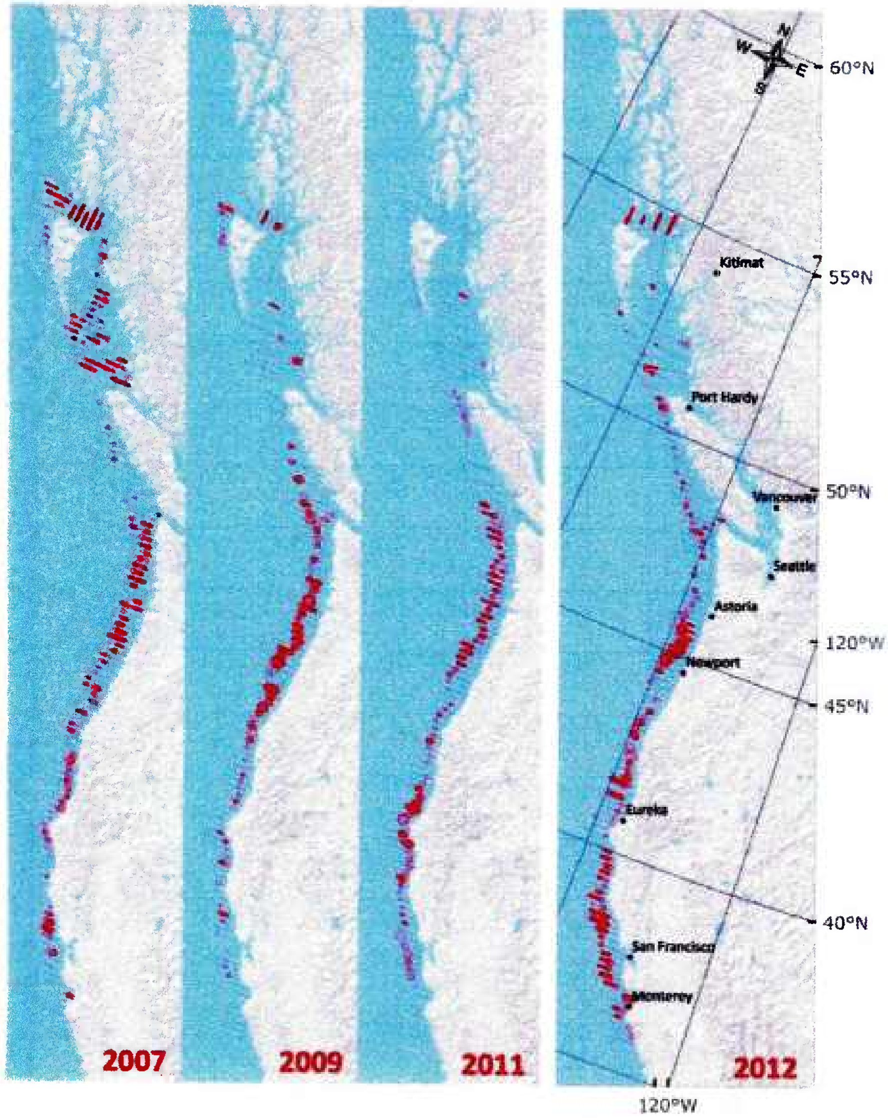
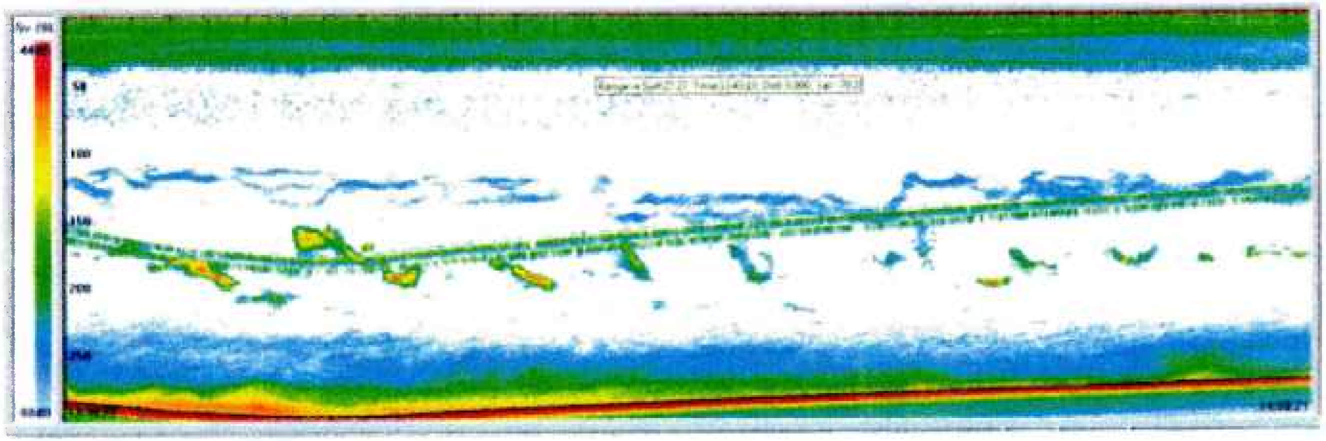


Figure 8 – Summertime geographic distributions of Pacific hake, as determined by NMFS/NWFSC. (Reprinted with permission of NMFS/NWFSC)

(a)



(b)

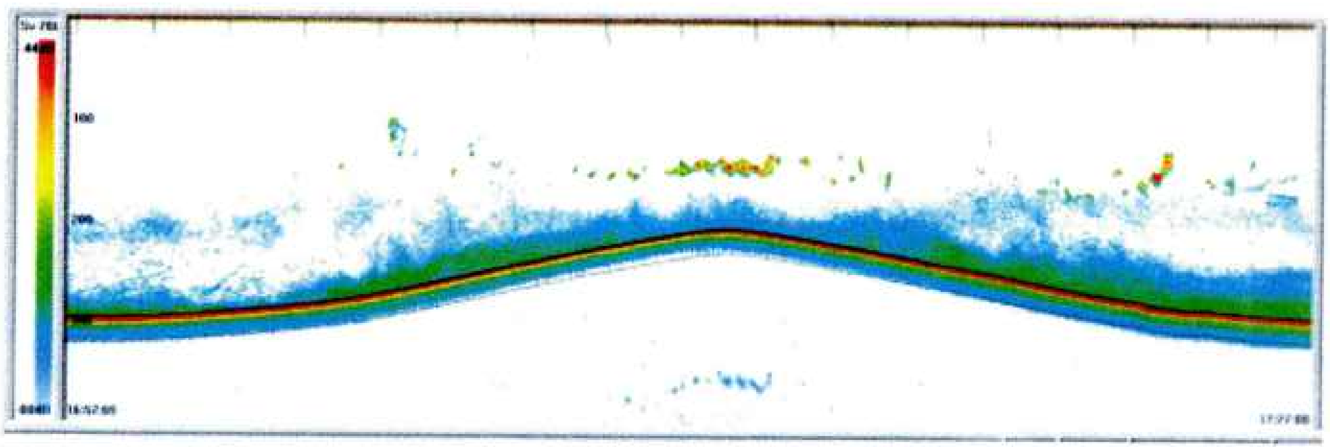


Figure 9 – New Horizon daytime 38 kHz echo sounder records showing high concentrations of hake-like targets. (a) Ship speed was 3.5 kt.
(b) Ship speed was 10.5 kt.

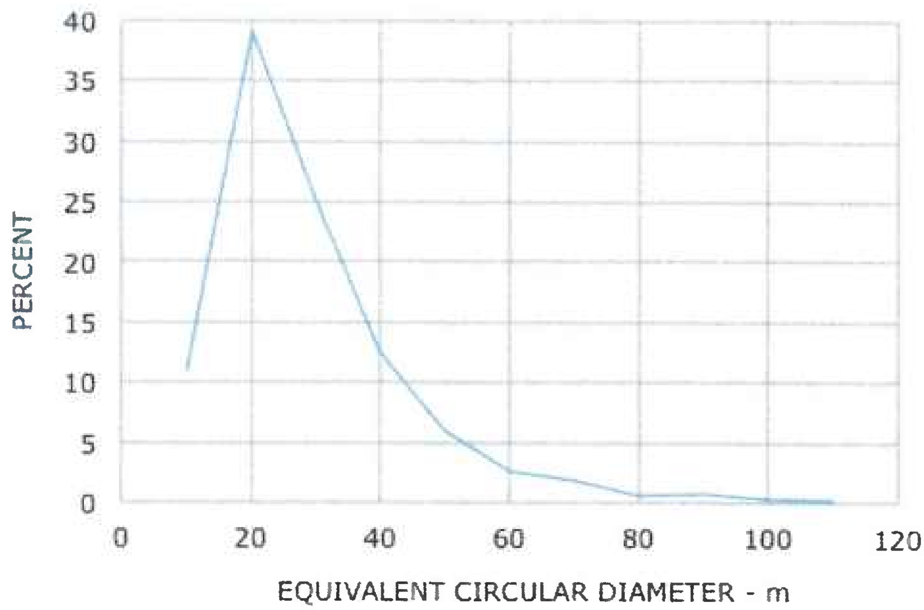


Figure 10 - Size distribution of Pacific sardine schools in 2012, as determined by NWASS

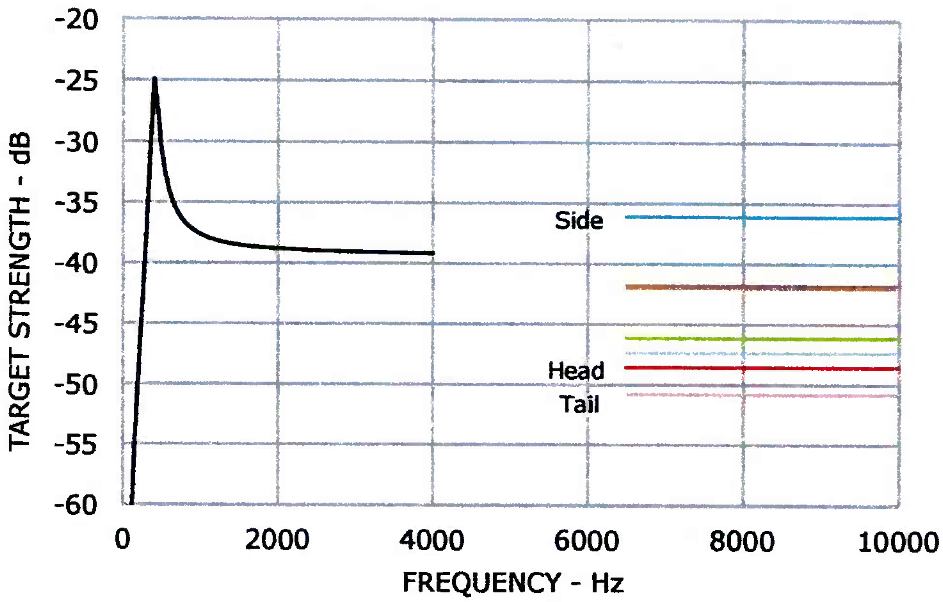


Figure 11 - Target strength of a 23 cm Pacific sardine at 7 m depth

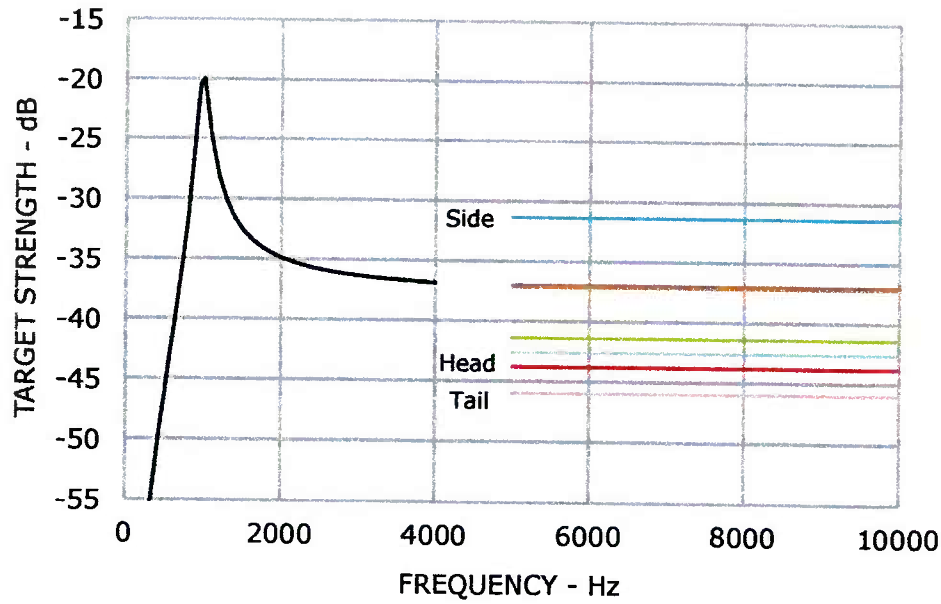


Figure 12a - Target Strength of a 40 cm Pacific hake at 150 m depth

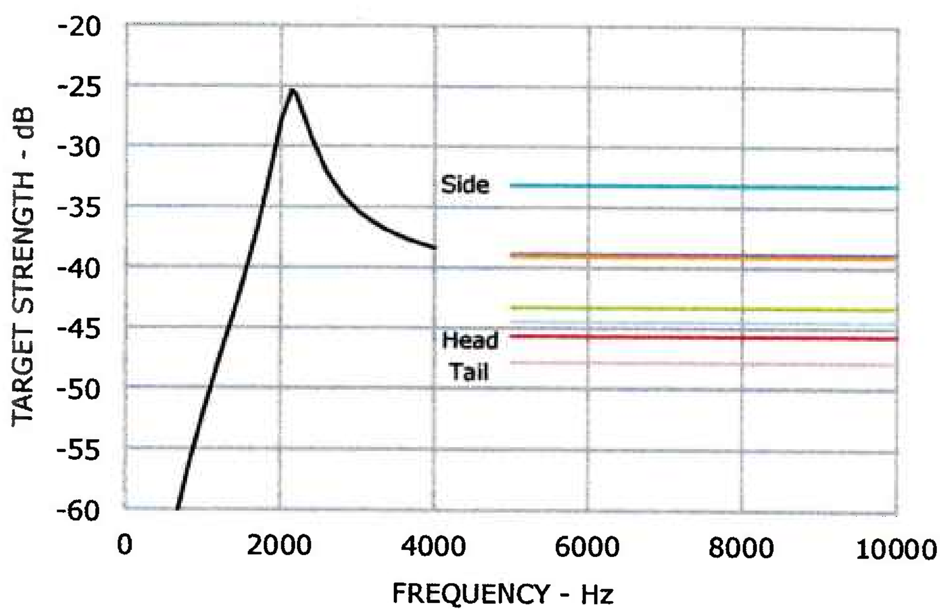


Figure 12b - Target strength of a 32 cm Pacific hake at 300 m depth